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Estimation of Characteristics, Methane Generated and Sustainability of Municipal Landfill Waste in Urban City, Thailand

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Abstract: Many developed and developing countries are concerned about climate change and greenhouse gas (GHG) reduction, with landfills being a major contributor due to the presence of important GHGs such as carbon dioxide (CO_2) and methane (CH_4) in landfill emissions. The appropriate technology or suitable innovation could result in the extraction of significant amounts of energy from CH_4 in landfills. This work used landfill gas emissions (LandGEM) software modeling to analyze the distribution patterns of the gas emissions of two urban landfills in Chonburi and Phuket Provinces, Thailand, from 2013 to 2023. The methane emissions from the Chonburi landfill were 1.063×10^4 Mg/year, and they were 1.077×10^3 Mg/year for the Phuket landfill, in 2023. According to estimates, the Chonburi landfill emitted 2.916×10^4 Mg/year of CO_2 in 2023, while Phuket emitted 2.955×10^3 Mg/year. The Chonburi landfill generated 8.67 MWh/year and 195.74 MWh/year of electrical energy potential from CH_4 in 2014 and 2023. In 2014 and 2023, the electrical energy potential from CH_4 was 1.00 MWh/year and 19.83 MWh/year for the Phuket landfill. This study's results show that landfills can produce CH_4 and that it is possible to collect this gas and stop GHG emissions from entering the atmosphere. This would be beneficial for local authorities considering the potential of landfill gas.

Keywords: methane; greenhouse gases; energy; landfill; recycling; urban areas; Thailand

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1. Introduction

Every day, humans generate and contribute to municipal solid waste (MSW), some of which is subjected to incineration or disposed of as landfill gas (LFG). Landfill gas is a natural byproduct of the decomposition of organic material in landfills. It is primarily composed of methane (CH_4), followed by carbon dioxide (CO_2) and trace amounts of other gases. The local authority collects and transfers MSW and then dumps it into a landfill, where it decomposes at the landfill site. Various studies have reported on the MSW-generated methane production, carbon dioxide, gas, and other toxic substances and their decomposition mechanisms [1–3]. In addition, leachates are toxic liquids in landfill gas, especially during the rainy season. Gas release and leachates could pose risks for human health and the environment. Recently, energy consumption, climate change, and environmental pollution have become significant issues for many countries, particularly in developing regions [4–7]. As urbanization and economic growth and consumption increase, solid waste generation has increased in many developing countries. Thailand is a developing country that is facing climate change and energy problems, and it has devoted efforts to reducing greenhouse emissions and increasing energy efficiency via several sources. Landfills can have a positive advantage for GHG reduction and energy potential, but they can also cause serious health problems if their design and management are not carefully considered. Most of the solid waste in Thailand is discarded through open dumping and landfill sites [8]. Industrial and urbanization areas are facing significant challenges due to the solid waste problem, which is growing every year. Chonburi and Phuket Provinces, with populations of approximately one million and four hundred thousand, respectively, are the most economic, industrial, and touristic cities in Thailand [8,9]. The high population concentration in these cities makes waste management a significant task [10]. There is no system for the separation and reuse of waste [10,11]. This is the main reason that these areas have been affected by a recent rise in GHGs and their impacts on the environment. Nowadays, municipal solid waste plays a significant role in landfill gas. Anthropogenic emissions from landfills contribute to greenhouse gases [12,13]. Thailand has announced that its GHG emissions will be reduced to 1.5 °C by 2030. Carbon-neutral and net-zero emissions are considered as a strategy for implementation in the future and will be used to reduce carbon emissions. Thailand aims to achieve carbon neutrality and net-zero GHG emissions by 2065 [14]. After reviewing various studies, we found that greenhouse gases such as perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and nitrogen trifluoride (NF_3) are released into the air and have an impact on climate change [14,15]. Landfill gas generates methane and CO_2 emissions through the degradation of organic matter, resulting in a higher proportion than other greenhouse gases [16]. Anthropogenic sources from landfill sites produce between 30% and 40% of all methane [6,17,18]. Landfill gas is a non-point-source emission; hence, the measurement of the emission rates of GHGs from landfills is essential to reduce uncertainties in the inventory estimates for this source. The predominant gases and toxic substances like CH_4 constitute around 50–60%, with 30% of CO_2. It also includes small amounts of ammonia (NH_3), hydrogen sulfide (H_2S), hydrogen (H_2), nitrogen (N_2), oxygen (O_2), and non-methane organic compounds (NMOCs) [19–21]. Landfill gas-to-energy has been applied in many models, and the potential of LandGEM has been discussed in the literature. The LandGEM model analyzes the annual emission rate using a first-order degradation (FOD) equation. The United States Environmental Protection Agency has recommended mathematical models for landfill gas estimation [22–24]. One of the most suitable and reliable ones used to estimate solid waste in landfill gas is the LandGEM model [22–24]. Solid waste quantification and the time period of the decomposition process are associated with methane and gas production [25,26]. The LandGEM model was used to estimate methane emissions at two landfill sites (open dumps) in Mumbai, India. Organic waste, paper, and rubber were the major waste components in these landfills. The average waste acceptance rate was 192,317 Mg/year (Deonar site) and 73,222 Mg/year (Mulund site). The results showed that the methane emissions were approximately 5630×10^6 m^3/year at the Deonar site and 5524×10^6 m^3/year at the Mulund site. The age of the landfill and the waste composition are the primary factors relevant to methane generation [27]. A similar study was conducted in Hamedan (Western Iran) from 2011 to 2030, where the LandGEM 3.02 model was used to predict gas emissions. Food and organic waste were the main components of the solid waste. The results showed that 4.371×10^8 m^3 of methane would be produced after 20 years, with most of it (4.053×10^6 m^3) occurring in the first year. Additionally, the methane production capacity at the Hamedan landfill site was 10^7 m^3/Mg [28]. Moreover, the methane emissions from the Mohammedia–Benslimane site in Morocco were analyzed using the LandGEM model. The characteristics of the landfill site, the waste composition, and the climatic conditions were studied. The study was conducted from 2012 to 2032. The methane generation was estimated to be 1.76 × 10^8 m^3. The electrical energy production at the landfill was estimated to be 1.78 × 10^7 kWh [29]. Another study was conducted at the Kanuru landfill in Vijayawada, India, using the LandGEM model to predict the methane emissions, potential renewable energy generation, and hydrogen production. The study covered the period from 2010 to 2020. The methane emission rate varied from 1.33 × 10^6 to 9.22 × 10^6 m^3. The annual energy production from landfill gas emissions ranged from 1.8 to 130 GWh/year, while hydrogen production ranged from 0.6 to 43.3 Gg/year [30]. Other models have been used to estimate landfill gas emissions, including a comparison between the Intergovernmental Panel on Climate Change (IPCC) method (a multiphase model) and the LandGEM model. The IPCC method and LandGEM are commonly used to estimate landfill gas. The total methane emissions from municipal solid waste were estimated at 23.17 Gg/year using the IPCC method and 5.74 Gg/year using LandGEM. Specifically, the IPCC method predicted a higher emission yield than the LandGEM model. This study estimated the emissions for the period from 2000 to 2020 [31]. Two models, namely LandGEM and Afvalzorg, were used to estimate the amount of landfill gas (LFG) emitted from the Africa landfill site. This study covered the period from 2005 to 2026. The methane and carbon dioxide emissions estimated by LandGEM were 3517 Mg/year and 9649 Mg/year, respectively, while the Afvalzorg model estimated the methane emissions at 3336 Mg/year [32]. Three models were applied to predict gas emissions at the Alexandria landfill site in Egypt: the LandGEM, Afvalzorg, and Mexico models. The Mexico model was designed with two scenarios for organic content: SC1, with 56% organics, and SC2, with 70% organics. The average gas emissions were 114 ± 60 m^3/year, 53 ± 28 m^3/year, 60 ± 27 m^3/year, and 65 ± 28 m^3/year for the LandGEM, Afvalzorg, Mexico SC1, and Mexico SC2 models, respectively. The LandGEM model provided higher estimates compared to the other models. These three models showed variations in their values [33]. Two landfill sites in Bangladesh were analyzed using six models: the modified triangular model (MTM), the IPCC zero-order decay model (ZODM), the IPCC first-order decay model (FODM), and in situ methods, along with various scenario analyses of the LandGEM model. The different scenarios of LandGEM included the LandGEM-Inventory Conventional (IC), LandGEM-Clean Air Act Conventional (CAAC), LandGEM-Inventory Wet (IW), LandGEM-Site-Specific (SP), and LandGEM-Site-Specific-1 (SP-1) models. This indicates that LandGEM can be used with site-specific data to estimate emissions, as well as with the default parameters. It is simple to use and shows insensitivity to uncertainties in some scenario analyses for the estimation of LFG. The results revealed that the LandGEM-SP1 model provided a similar estimation to the direct measurement (in situ) method for methane (CH_4), with values of 25.95 Gg/year and 19.02 Gg/year, respectively [24]. The LandGEM default method (DM), first-order decay method (FOD), and modified triangular method (MTM) were used to predict the methane emission rates between 2020 and 2050 in India. The results regarding methane emissions for LandGEM, DM, FOD, and MTM were 453.79 Gg, 557.6 Gg, 384.44 Gg, and 397.28 Gg, respectively. It was found that the DM provided higher values than the other models, and the variable parameters input into the model were key factors [34]. The ratio of organic composition, the morphology of the stored waste, and the atmospheric pressure, air temperature, landfill storage and density, and percentage of moisture influence the differences in gas production at a landfill site [35]. The LandGEM model enables the estimation of CH_4 gas emissions from landfills in Thailand, thereby contributing to the reduction of both national and global greenhouse gas emissions. In recent years, extensive research has been conducted on the use of electrical energy from landfill gas, highlighting its importance in promoting strategies for GHG reduction and energy recovery. The landfill gas can be traded in the carbon credit market [6,7,21]. The aim of this study was to estimate the GHG emissions from the Chonburi and Phuket landfill gas in Thailand and the waste-to-energy from landfills through municipal solid waste data over a 10-year (2013–2023) period using the LandGEM model, version 3.03.

2. Results

2.1. Landfill Site, Characteristics, and Waste Generation

We calculated the results regarding the waste accepted and waste in place for two urban landfills. As shown in Tables 1 and 2, the term "waste accepted" refers to the transfer of all waste to dumps in landfills, followed by its compacting in the landfill as waste in place. The waste generation in the cities of Chonburi and Phuket from the years 2013 to 2023 is presented in Tables 1 and 2. This work selected the landfill sites based on their characteristic areas, waste amounts, and waste management. The first year of the time period was 2013; the end of this period was 2023. Since the LandGEM software model uses these data to calculate the amounts of gases such as CH_4, CO_2, and NMOCs, it is important to accurately estimate the weight of the produced waste in different years. The results indicated the disposed solid waste quantity for the Chonburi landfill during the 10 years of open landfilling. The amount of disposed municipal waste produced was estimated at 84,912 Mg in 2013, which increased to 321,459 Mg in 2023, whereas, for the Phuket landfill, the amount of disposed municipal waste produced was approximately 9824 Mg in 2013, which increased to 46,807 Mg in 2023. The year 2022 showed the highest accepted waste value of 321,459 Mg/year in the Chonburi landfill. In 2019, the Phuket landfill recorded the highest accepted waste value of 49,689 Mg/year. The total quantity of disposed waste at the two urban sites is rapidly increasing due to the significance of the selected sites as tourist areas, population growth, industrialization, and urbanization. However, in other countries, the amount of disposed waste at such sites is significantly higher [31,36,37]. The Chonburi landfill accepts more waste than the Phuket landfill because of the potential population impact on waste disposal. The total amount of disposed waste estimated at the Chonburi landfill was 2,516,359 short tons by the year 2023. For Phuket, the total amount of disposed waste estimated by the year 2023 was 264,472 short tons (Table 1).

Table 1. The amount of waste accepted and in place at the Chonburi landfill.

Year	Waste Accepted		Waste in Place	
	(Mg/Year)	(Short Tons/Year)	(Mg/Year)	(Short Tons/Year)
2013	84,912	93,404	0	0
2014	180,720	198,792	84,912	93,404
2015	200,447	220,492	265,632	292,195
2016	213,488	234,837	466,080	512,687
2017	214,753	236,228	679,568	747,524
2018	233,342	256,676	894,320	983,752
2019	256,100	281,709	1,127,662	1,240,429
2020	270,063	297,069	1,383,762	1,522,138
2021	312,316	343,548	1,653,825	1,819,207
2022	321,459	353,605	1,966,141	2,162,755
2023	287,364	316,100	2,287,600	2,516,359

Table 2. The amount of waste accepted and in place at the Phuket landfill.

Year	Waste Accepted		Waste in Place	
	(Mg/Year)	(Short Tons/Year)	(Mg/Year)	(Short Tons/Year)
2013	9824	10,806	0	0
2014	47,267	51,994	9824	10,806

Table 2. *Cont.*

Year	Waste Accepted		Waste in Place	
	(Mg/Year)	(Short Tons/Year)	(Mg/Year)	(Short Tons/Year)
2015	12,305	13,536	57,091	62,800
2016	16,646	18,311	69,396	76,336
2017	13,236	14,559	86,042	94,646
2018	32,689	35,957	99,278	109,206
2019	49,689	54,658	131,966	145,163
2020	32,088	35,296	181,655	199,821
2021	5731	6304	213,743	235,117
2022	20,955	23,051	219,474	241,421
2023	42,552	46,807	240,429	264,472

2.2. Methane Generation from Municipal Solid Waste

The previous section described the LandGEM landfill gas model, which requires the input of specific parameters, such as the methane generation index (k = 0.05 (1/year)), potential methane generation (L0 = 170 (m^3/Mg)), and other NMOC gases at a concentration of 4000 ppm [6]. The study period for these two landfills, which are still in operation, spanned from 2013 to 2023. During the first year of the study, the LandGEM model did not have a performance emission rate, meaning that there was no gas escape from waste landfill [7,38]. Table 3 presents the estimation results for CH_4 produced at the Chonburi landfill in various years over the given period. Furthermore, Table 3 shows that the total gas varied from 1.33×10^4 to 9.325×10^3 Mg/year in 2013–2023. The methane production process over various years was studied in the Chonburi landfill; this landfill produced methane amounting to around 1.063×10^4 Mg/year. In addition, Table 4 shows the results of methane estimation in the Phuket landfill, which produced methane of around 5.447×10^1 Mg/year. The total gas varied from 1.175×10^3 to 92.039×10^2 Mg/year in 2013–2023. Several gases, including CO_2 and NMOCs, are also presented in Tables 3 and 4. Landfills also generate pollutants such as CO_2 and NMOCs, while GHGs release gases into the atmosphere, contributing to climate change. This work applied the LandGEM model and analyzed the amounts and emission rates of CO_2 and NMOCs; the result was lower than that for CH_4. Table 3 shows that the CO_2 generated was around 2.916×10^4 Mg/year for the Chonburi landfill site and 2.955×10^3 Mg/year for the Phuket landfill site (Table 4). Compared to CH_4 and CO_2, NMOCs generated smaller amounts, with estimates of 4.567×10^2 Mg/year and 4.629×10^1 Mg/year. Other results indicate the trends in gas production, including CH_4, CO_2, and NMOCs (in m^3/year), in different years of the study period at the waste disposal sites of Chonburi and Phuket. Figure 1 shows that the amount of CH_4 produced was 7.058×10^5 m^3/year and 1.593×10^7 m^3/year in 2014 and 2023 at the Chonburi landfill. Similarly, the CO_2 production amounted to 7.058×10^5 m^3/year and 1.593×10^7 m^3/year in 2014 and 2023, whereas the NMOC production was 5.646×10^3 m^3/year and 1.274×10^5 m^3/year, respectively. Figure 2 shows that the amount of CH_4 production was 8.165×10^4 m^3/year and 1.614×10^6 m^3/year in 2014 and 2023 at the Phuket landfill. Similarly, the CO_2 production was 8.165×10^4 m^3/year and 1.614×10^6 m^3/year in 2014 and 2023, whereas the NMOC production was 6.532×10^2 m^3/year and 1.292×10^4 m^3/year, respectively.

Table 3. Estimation of gas production at the Chonburi landfill.

Year	Total Landfill Gas (Mg/Year)	Methane Gas (Mg/Year)	Carbon Dioxide (Mg/Year)	NMOCs (Mg/Year)
2013	0	0	0	0
2014	1.763×10^3	4.709×10^2	1.292×10^3	2.024×10^1
2015	5.428×10^3	1.450×10^3	3.978×10^3	6.233×10^1
2016	9.325×10^3	2.491×10^3	6.834×10^3	1.071×10^2
2017	1.330×10^4	3.553×10^3	9.749×10^3	1.527×10^2
2018	1.711×10^4	4.571×10^3	1.254×10^4	1.965×10^2
2019	2.112×10^4	5.642×10^3	1.548×10^4	2.425×10^2
2020	2.541×10^4	6.787×10^3	1.862×10^4	2.917×10^2
2021	2.978×10^4	7.953×10^3	2.182×10^4	3.418×10^2
2022	3.481×10^4	9.297×10^3	2.551×10^4	3.996×10^2
2023	3.978×10^4	1.063×10^4	2.916×10^4	4.567×10^2

Table 4. Estimation of gas production at the Phuket landfill.

Year	Total Landfill Gas (Mg/Year)	Methane Gas (Mg/Year)	Carbon Dioxide (Mg/Year)	NMOCs (Mg/Year)
2013	2.039×10^2	0	0	0
2014	1.175×10^3	5.447×10^1	1.495×10^2	2.341×10^0
2015	1.373×10^3	3.139×10^2	8.613×10^2	1.349×10^1
2016	1.652×10^3	3.668×10^2	1.007×10^3	1.577×10^1
2017	1.846×10^3	4.413×10^2	1.211×10^3	1.897×10^1
2018	2.435×10^3	4.931×10^2	1.353×10^3	2.120×10^1
2019	3.348×10^3	6.503×10^2	1.784×10^3	2.795×10^1
2020	3.850×10^3	8.942×10^2	2.453×10^3	3.843×10^1
2021	3.782×10^3	1.028×10^3	2.822×10^3	4.421×10^1
2022	4.032×10^3	1.010×10^3	2.771×10^3	4.342×10^1
2023	2.039×10^2	1.077×10^3	2.955×10^3	4.629×10^1

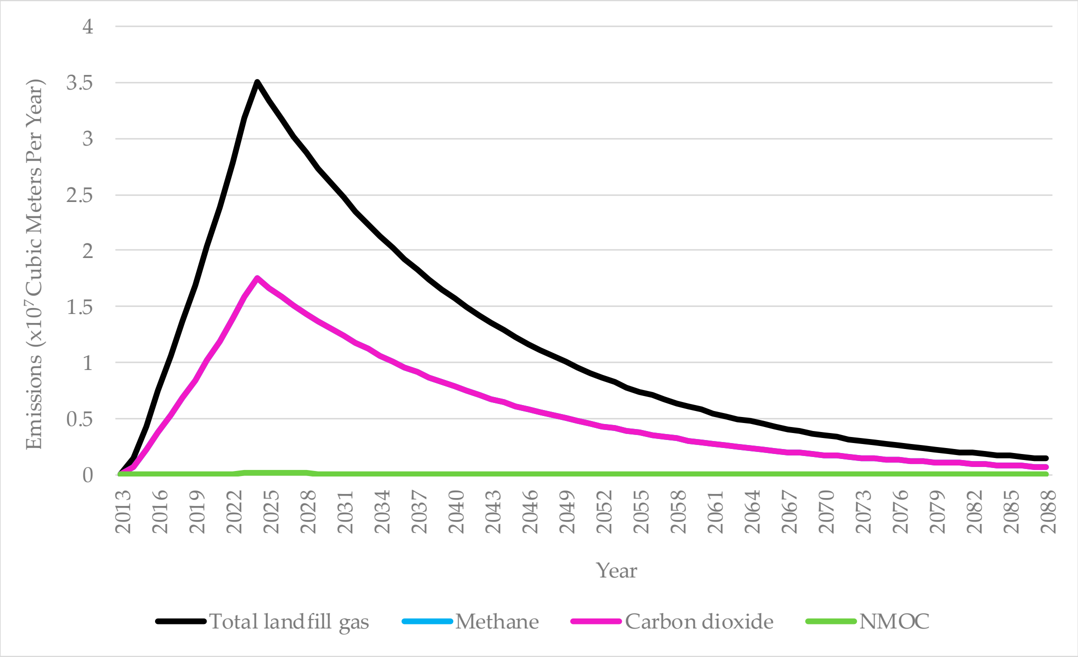

Figure 1. Emission rates of CH_4, CO_2, and other NMOC gases (m^3/year) in Chonburi landfill.

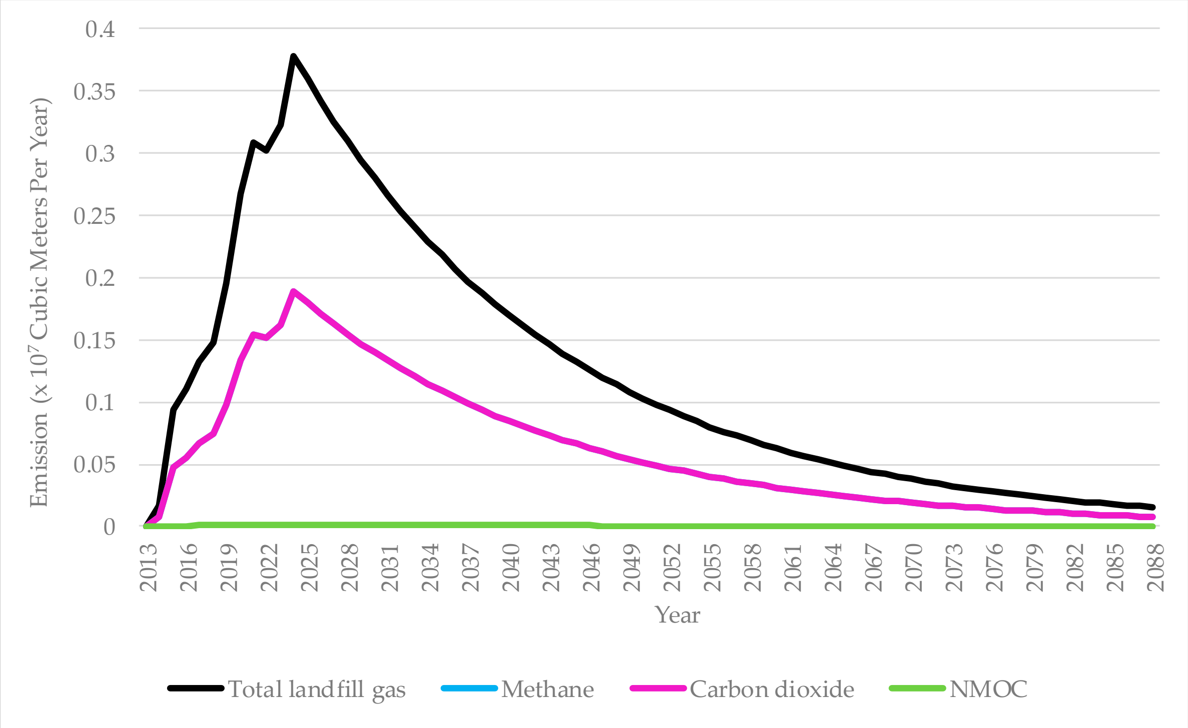

Figure 2. Emission rates of CH_4, CO_2, and other NMOC gases (m^3/year) in Phuket landfill.

2.3. Energy Production and Sustainability

Figures 3 and 4 illustrate the successful outcome of using CH_4 to generate electricity from the two urban landfills. The energy production result was calculated from Equation (2), and the energy production values are presented for 2014 to 2023. The electrical energy of CH_4 gathered from landfill gas is increasing with time. In 2014, the Chonburi landfill generated 8.67 MWh/year of potential electrical energy. By 2023, the landfills generated approximately 195.74 MWh/year of electrical energy (Figure 3). Similarly, the Phuket landfill generated 1.00 MWh/year of electrical energy from CH_4. In 2023, the recovered landfill methane generated 19.83 MWh/year, as shown in Figure 4. These two urban landfills were different due to the amounts of methane derived from dumped waste. The energy potential may reach the rate of methane emission. Anaerobic digestion can recover the energy production potential from waste. Based on the results, the amount of electrical energy produced in the urban landfills was determined, which highlights the possibilities and sustainability of MSW in accordance with the SDGs. The SDGs are very popular sustainability principles set forth by the United Nations (UN). The principle of leaving no one behind underpins the SDGs' agenda, as countless individuals find themselves in extreme states of insecurity or vulnerability. For example, SDGs 12 and 13 pertain to sustainable consumption and production, while SDG 13 deals with climate change and its consequences.

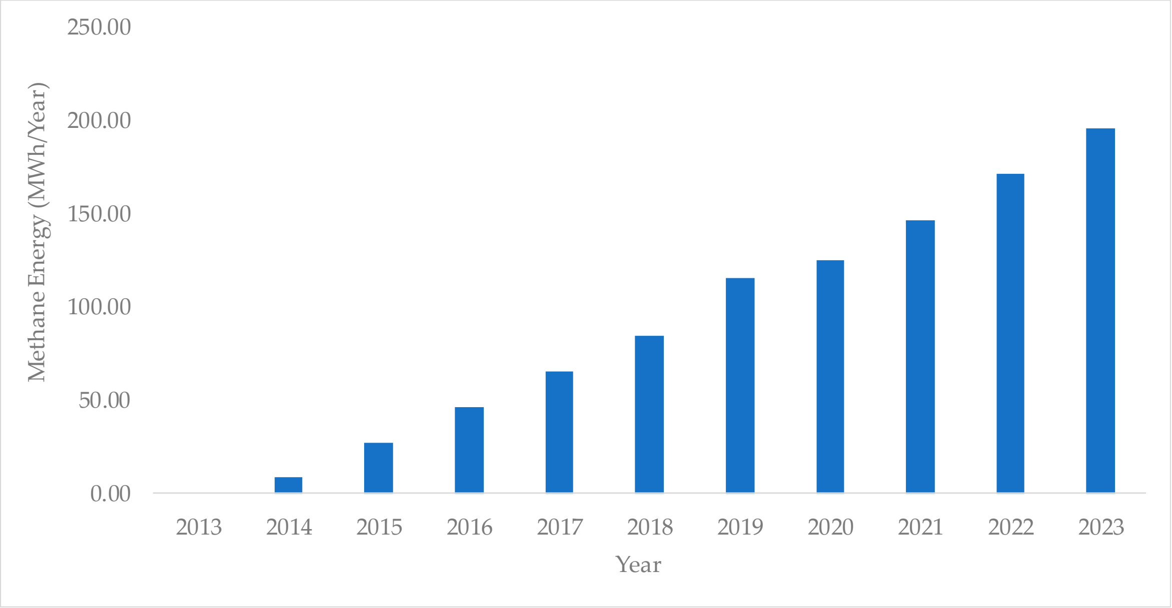

Figure 3. Energetic potential of methane from Chonburi landfill.

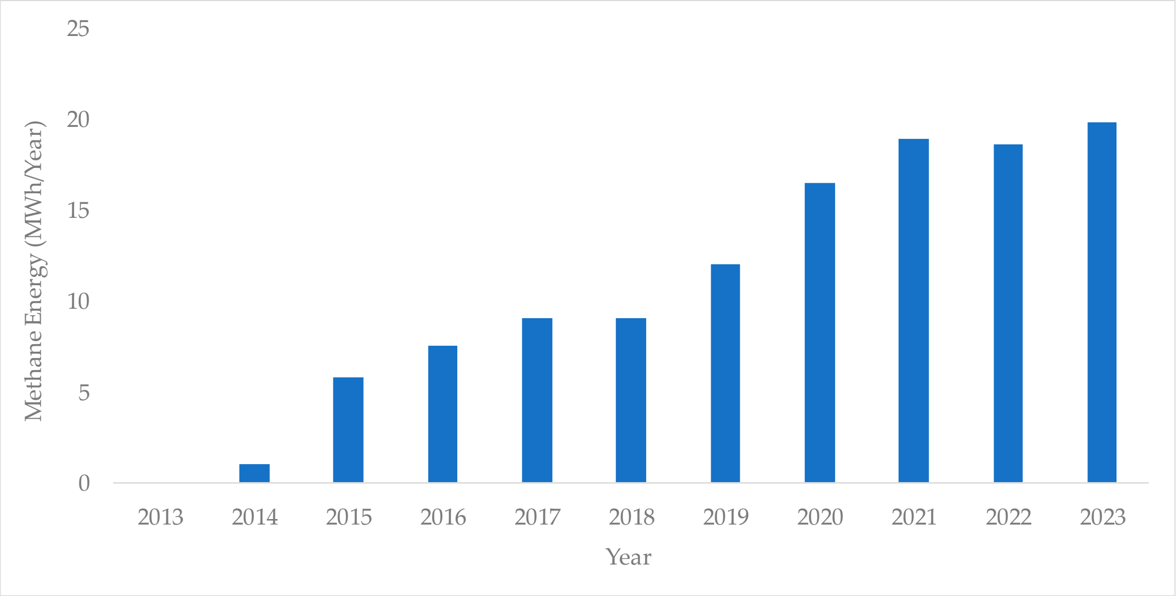

Figure 4. Energetic potential of methane from Phuket landfill.

3. Discussion

Due to the lack of a waste collection organization, open dumping dominates waste management in Thailand, despite being neither the optimal solution nor a sustainable way to handle MSW. Therefore, it is common for waste disposal in urban disposal sites (landfills and open dumping) to generate CH_4 emissions, as well as CO_2 and NMOCs. In this work, the methane potential production varied from 1.063×10^4 Mg/year to 4.709×10^2; the highest value was 8.942×10^2 Mg/year in 2020 according to the LandGEM model at the Chonburi landfill, which was higher than that of the Phuket landfill. The LandGEM model's accuracy in relation to the input parameters could potentially increase the uncertainty in the CH_4 emissions. The two most important parameters are the methane generation rate (k) and methane generation capacity (L0). Often, we may use default values when the actual input parameters are absent [7]. In another study, Fallahizadeh et al., in 2019, showed that the landfill methane emissions in Iran varied within 250–330 m^3/h, respectively, which were obtained from methane production rates that were obtained during the years 2009–2012 [6]. Similarly, a study in Malaysia was conducted during 2012–2015, and the result showed 4.436 × 10^2 (Mg/year) of methane production and about 4.17 × 10^3 (Mg/year) for the end of the year [39]. The LandGEM model was applied for methane estimation at an open dumpsite in Pakistan in the period of 1992–2021, and the total methane emissions were found to be 1.354 × 10^8 m^3/year. The methane production rate associates the organic waste in the landfill with the period of time [40]. The LandGEM model was used to study the municipal solid waste deposition in three landfills in Delhi, India, to predict the CH_4 emissions from 2009 to 2015; the cumulative CH_4 was 56.45 G/y in 2015. These three landfill sites continue to operate and receive waste from all over Delhi, and the time period aligned with our study [41]. On the other hand, in 2042, the maximum methane predicted by the LandGEM model was 1.66 × 10^7 m^3/year [42]. For 2010–2030, the average rate of methane emissions was predicted to be 4.58 Mg/year for a landfill in Kanpur City [43]. Another study in India considered gas production and electricity from landfills in Trichy and Thanjavur. As a result, the Trichy landfill produced the most landfill gas emissions in 1993, while the Thanjavur landfill was predicted to produce the most in 2027. The results regarding the CO_2, CH_4, and gas predictions were 16.2 × 10^{10}, 8.2 × 10^{10}, and 16.2 × 10^{10} m^3/year for Trichy in 1993 and 13 × 10^6, 5 × 10^6, and 13 × 10^6 m^3/year for the Thanjavur landfill in 2027 [5]. The Trichy landfill had the potential to generate 1.22 × 10^7 and 4.33 × 10^7 kWh/year of electrical energy for 2020 and 2063 [5]. In 2020 and 2052, the Thanjavur dumpsite was predicted to generate 1.14 × 10^7 and 3.87 × 10^7 kWh/year of electrical energy, respectively [5]. In another study, electrical potential was generated from waste landfill at 11.88 MWh/year [36]. The GHGs generated directly from municipal solid waste can affect climate change and energy generation. Enhancing appropriate landfill management could be a potential strategy for power production or to address environmental concerns. In our study, there was the potential to generate 195.74 MWh/year and 19.83 MWh/year of electricity in 2023 for the Chonburi and Phuket landfills. Moreover, waste management via waste-to-energy landfills [43,44] not only reduces the daily increase in waste production but also adds value to waste [41]. It serves as the cornerstone of a circular economy for communities, revitalizing waste by transforming it into renewable energy [45–47]. At the same time, this method can help to solve the problem of overflowing waste and reduce landfills, resulting in energy sustainability. The United Nations (UN) has established the concept of the sustainable development goals (SDGs), which comprise a total of 17 goals. Our work was associated with SDG 12, specifically goal 12.5, which describes sustainable production, recycling, reuse, and waste reduction, as well as goal 13, which aims to reduce GHGs [47]. The SDGs relate climate change and climate action. The global temperature rise must be reduced to less than 1.5 degrees Celsius [48]. This work could serve as guidance to support SDGs 12 and 13 [49]. The application of municipal solid waste decomposition, particularly landfill gas recovery systems, will be crucial in the future to reduce the volume of waste disposed of in landfills. In general, landfill gas (LFG) is processed in three stages. First, LFG is extracted from the landfill using a series of wells and a blower/flare (or vacuum) system. This step removes moisture as the gas passes through a knockout pot, filter, and blower (primary treatment). Next, the treatment involves using an aftercooler or other moisture removal methods, followed by siloxane/sulfur removal and compression. Finally, advanced treatment removes additional impurities (such as CO_2, N_2, O_2, and VOCs) and compresses the LFG into a high-Btu gas that can be used to generate electricity, serve as vehicle fuel, or be injected into a gas pipeline [50,51]. The benefits of municipal solid waste from landfills include electricity generation and its potential use for households. Additionally, it can serve as fuel for electricity production and as an alternative fuel for vehicles. From environmental, social, and economic perspectives, it can also be traded in the carbon credit market due to the capture of greenhouse gases. However, investors and local authorities must understand the mechanisms of the carbon market for landfills to fully utilize these opportunities.

4. Materials and Methods

4.1. Study Areas and Waste Characterization

The municipal solid waste (MSW) generation system in Thailand is increasing every year, especially in urban areas such as the Bangkok Metropolitan Region [8]. This study used the MSW characteristics of selected urban cities in Thailand, specifically Laem Chabang in Chonburi Province and Phuket City in Phuket Province, as shown in Figure 5. Table 5 provides the sorting of the waste categories. Common MSW components include plastic bags, foam, paper, rubber, wood, grass, metal, glass, and food waste. Incineration or the use of landfill gas can be implemented in the municipal solid waste system in Phuket and Chonburi. It possesses the capacity to handle substantial amounts of waste. The wet mass basis of MSW revealed average moisture content of approximately 55%. According to reports [9,10,36], Phuket's waste quantity approximated 5 kg/capita/day. In Scenario 1, Phuket City in Phuket province operated a landfill with a useful life of 10 years, which began operations in 2013 and was projected to end in 2023. Phuket is located in the southern part of Thailand; it is an island city and tourism area. MSW was collected from the city and transported to the landfill site. Laem Chabang, in Chonburi Province, represented Scenario 2, where waste was disposed of in a landfill with a useful life of 10 years, operating from 2013 to 2023. The landfill was owned by the city municipality, while a private venture held the legal rights to use the biogas produced. This situation is typical of urban cities. This region is located in the east of Thailand, characterized by industrialization and urbanization. We characterized the weather and climate in the two study areas. Phuket Province has mountains, large and small islands, and sandy beaches. It is warm in Phuket all year round, with temperatures ranging between 25 and 34 °C. Phuket typically has two different seasons, dry and wet, with transitional periods in between. The wet season starts in June and ends in October. This is Phuket's low season. The mean precipitation in Phuket is approximately 2500 mm, predominantly occurring during this timeframe. The conditions are hot, humid, and moist [52]. Chonburi Province is primarily characterized by mountains, numerous large and small islands, and surrounding industries. The average temperature was recorded at 27.5 °C, with 1269 mm of rainfall. Chonburi Province has three clearly distinguished seasons (winter, rainy, and summer). However, the amount of MSW in Phuket and Chonburi is increasing annually, and, in order to reduce the waste and greenhouse gas emissions, there is a need to enhance the waste management capabilities. MSW is separated in two ways, with the first option being its transfer to the station for the thermochemical process and the second involving its collection and transfer to the biochemical process. The common flowchart for waste-to-energy technologies is shown in Figure 6 [53–55].

Table 5. Summary of waste categories in landfill [9,26].

Waste Category	Material Types
Common waste	Non-recyclable plastics, plastic bags, plastic packaging, foam
Organic waste	Food waste, wood, residual biomass

Table 5. *Cont.*

Waste Category	Material Types
Recyclable waste	Recyclable plastics, glass, PET bottles, glass bottles, paper, paper boxes
Hazardous waste	Hospital waste, agricultural waste such as pesticides and insecticides, other waste (batteries, chemical containers)

Note: The types of municipal solid waste in general landfills include waste from households, offices, hotels, shops, schools, and other institutions in Thailand.

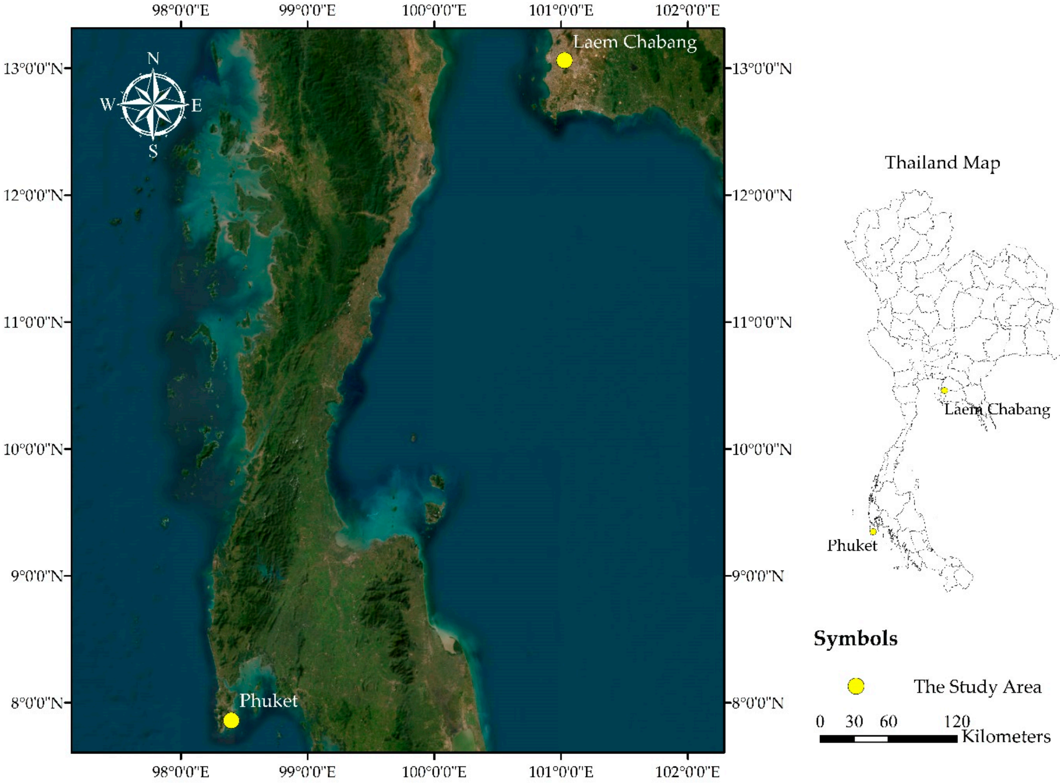

Figure 5. Locations of municipal solid waste facilities.

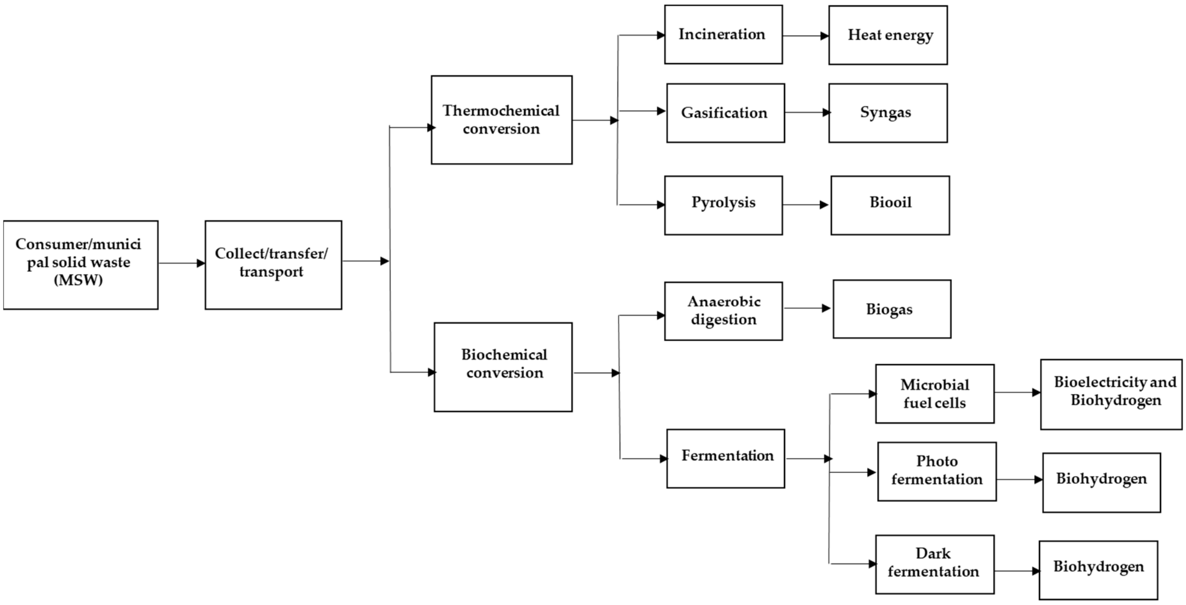

Figure 6. A common flowchart for municipal solid waste-to-energy technologies is presented. LandGEM was used to analyze the processes using biochemical conversion.

4.2. LandGEM 3.03 Model

LandGEM is a mathematical software model used to estimate the gas production, such as CO_2 and CH_4, at landfills [6,21,28]. This model uses a first-decay-rate equation developed by the US EPA. The US EPA's specialists extended the LandGEM model, which is reliable, easy to use, and free to access [6]. The LandGEM model uses data based on site-specific information from landfills. The LandGEM model is outdated as it was created in 1996, with the last update in 2023 with version 3.03. Many landfills in many areas have used the LandGEM model to estimate waste masses and methane emissions. The municipal solid waste in landfills is almost homogeneous, but the organic waste composition has a significant impact on methane generation compared to other types. The LandGEM model uses important factors to evaluate the methane generation rate (k) and potential methane generation capacity (L_0), which are used in the model to estimate LFG.

4.3. Necessary Data Input to LandGEM 3.03 Model Equation

This work obtained the characteristics of LFG from local authorities to input into the LandGEM model, such as the solid waste amount, landfill start year, and landfill closure year. The LandGEM model calculated the most important parameters, i.e., the methane generation rate (k/year) and methane yield (L_0) (m^3/Mg). The model assumes that methane and carbon dioxide, which make up 100% of the total pollution, and all other pollutants fall under the less than 1% category, indicating that NMOCs have no impact on the calculation. The starting year and closing year are determined by the characteristics of the landfill, and this work spanned from 2013 to 2023. The study period for the Chonburi and Phuket landfills spanned 10 years, making it a suitable evaluation period for LandGEM. Although the landfills are closing, LFG will continue to be emitted for several more years. The LandGEM model employs the following equations. The model software uses the first-order decomposition rate equation to measure the emissions over a specific time. The following decomposition equation uses the model parameters k and L_0 [6]. This work used the current LandGEM software, version 3.03.

$$\boldsymbol{Q_{CH4}} = \sum_{i=1}^{n}\sum_{j=0}^{n} kL_0\left(\frac{M_i}{10}\right)\mathrm{e}^{-kt_{ij}} \tag{1}$$

where Q_{CH4} refers to annual methane generation, m^3/year; i is a one-year time increment; n is the year of calculation—the initial year of waste acceptance; j is a 0.1-year time increment; k is the methane generation rate, $year^{-1}$; L_0 is the potential methane generation capacity, m^3/Mg; M_i is the weight of waste accepted in the ith year; M_g is the age of the jth section of waste; M_i is the waste accepted in the ith year (decimal years—for example, 3.2 years).

4.4. Calculation of Electrical Energy Production Potential

The electrical energy (kWh/year) from the CH_4 amount of gathered landfill gas can be computed by the following Equation (2) [21,56]:

$$\boldsymbol{E_p}\ (kWh/year) = \frac{\mathrm{LHV}_{CH4}\ \times 0.9 \times Q_{CH4} \times \lambda \times \eta}{3.6} \tag{2}$$

where LHV_{CH4} is the lower heated amount of CH_4 and is given as 37.2 MJ/m^3, Q_{CH4} is the amount of methane produced each year in mg/year, 3.6 is the conversion factor from MJ to kWh, λ is the collection output of 60% [57], and η is the electrical output for the internal ignition engine, given as 33% [44].

5. Limitations

The present assessment incorporated the physical characterization of waste from two urban cities from a 2023 scientific study into the LandGEM model, which presented significant limitations. In some cases, the characteristics of municipal solid waste can vary annually. Therefore, it would be more appropriate to characterize municipal solid waste based on the current conditions and incorporate these refined values into the LandGEM model for accuracy. Previous studies have reported that, to avoid uncertainty in the LandGEM model, researchers should use the default parameters and site-specific parameters to estimate the energy generation [44,58]. This could be another possible limitation. Furthermore, the LandGEM model's use of parameters K and L_0 poses a significant limitation due to potential changes over time.

6. Conclusions

This study used mathematical software model to estimate the GHGs, such as CH_4 and other gases, from 2013 to 2023 using the LandGEM model, version 3.03. The total CH_4, CO_2, and NMOC emissions were evaluated using the LandGEM model. The methane emissions from the Chonburi landfill were 1.063×10^4 Mg/year, and they were 1.077×10^3 Mg/year for the Phuket landfill, in 2023. According to estimates, the Chonburi landfill emitted 2.916×10^4 Mg/year of CO_2 annually in 2023, while Phuket emitted 2.955×10^3 Mg/year. Waste landfill also produced NMOC emissions; the result for the Chonburi landfill was 4.567×10^2 Mg/year, while it was 4.629×10^1 Mg/year for the Phuket landfill in 2023. The Chonburi landfill generated 8.67 MWh/year and 195.74 MWh/year of electricity from CH_4 in 2014 and 2023. In 2014 and 2023, the electrical energy potential from CH_4 produced 1.00 MWh/year and 19.83 MWh/year for the Phuket landfill. These results suggest that it is not only possible to estimate the GHG emissions, but there is also potential to generate electricity and promote sustainable energy recovery at landfill sites. This approach proposes directions for landfill gas management to reduce emissions from landfill surfaces, such as cogeneration (CHP), biomethane, biohydrogen production, and methane volatilization. Landfills can help to reduce energy costs and can also be used to generate income. However, if MSW is not properly collected, transferred, and managed, huge quantities of methane could be released into the atmosphere, negatively impacting the air quality and contributing to global warming. The results of this study could be adopted by local authorities and the government to consider GHG emissions and energy production at these two urban landfill cities. Additionally, this study is aligned with the sustainable development goals, namely SDG 13 and SDG 7, which are related to climate change and energy recovery. Moreover, waste management is the foundation of a circular economy, giving waste renewed usefulness by converting it into renewable energy. This presents a significant opportunity for energy generation. The findings of this research provide significant knowledge that could enhance our understanding of GHG control and energy potential production from waste landfill sources. For further research, it is necessary to consider how landfill gas (LFG) can be captured, converted, and used as a renewable energy resource, which could be considered for the carbon credit market.

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